Couvalis, George 2001. Claudius Ptolemy (Klaudios Ptolemaios) and the Sphericity of the Earth.
In E. Close, M. Tsianikas and G. Frazis (Eds.) “Greek Research in Australia:
Proceedings of the [3rd] Annual Conference of Greek Studies, Flinders University, 23-24 June 2000”.
Flinders University Department of Languages – Modern Greek: Adelaide, 28-38.

Claudius Ptolemy (Klaudios Ptolemaios) and the Sphericity of the Earth

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We are, as Neugebauer puts it, in the fortunate position that we know almost nothing about Claudius Ptolemy except that he was a Greek scientist who lived and worked in Alexandria in the second century of the common era (CE) (Neugebauer, 1975:834). We have to study his scientific works and not extraneous material about his dining habits or his love life. His important work was done about 150 CE. He produced important surviving contributions in optics, harmonics and other areas. He produced a work on astrology, regarded as an important science in antiquity. However, his most significant contributions were in geography and astronomy. In both areas, he produced texts which were to survive as the canonical texts for more than twelve hundred years. With the exception of Euclid’s (Euklides’) Geometry, some of the works of Archimedes on Statics and Galen’s (Klaudios Galenos’) anatomical works, they are the only western scientific works to be central texts for anything like this period of time. Although earlier Babylonian and Greek researchers had done reasonably precise mathematical work in astronomy or geography, the detailed assimilation of rough empirical data into a mathematically precise work by Ptolemy far surpasses anything we know to have existed in antiquity in these areas. He relied to some degree on work done by Hipparchos (fl.150 before the common era [BCE]), whom he mentions many times. There has been a longstanding debate as to the degree to which Ptolemy is dependent on Hipparchos. The general scholarly consensus is that although he learnt much from Hipparchos, Ptolemy produced some fundamental breakthroughs and worked out many of the details which were necessary to make Hipparchos's system work.[1] For my purposes, it does not matter whether Ptolemy's work is the culmination of a post-Aristotelian astronomical and geographical tradition in which Hipparchos is the central figure or whether Ptolemy is the central figure in that tradition.

The quality of the work of Hipparchos and Ptolemy was not widely understood in the period following the scientific revolution of the seventeenth century because the dominant tradition of historical writing about science was a "whiggish" scientific hagiography. This tradition aimed to produce edifying stories about the great figures who discovered fundamental principles and facts. Scientists like Ptolemy, who had been mistaken about the nature of the solar system and the movement of the earth, were often regarded as enmeshed in scholastic *a priori* dogmas or ignorant of obvious empirical facts.[2] In the twentieth century, serious historical work showed that Ptolemy was an important figure who had done very significant work in astronomy and geography. However, by and large, his contribution was seen as mathematical and geometrical. Methodologically, he was usually thought to be just a follower of Aristotle or some other great figure. His broader scientific contribution was also thought to be minor.

Two views have been common amongst historians and philosophers of science in recent times. The first and more popular view presents Aristotle as laying the foundations of ancient and medieval science and sees the revival of the study of Aristotle in western Europe in the thirteenth century as laying the groundwork for the seventeenth century scientific revolution. On this view, Aristotle was wrong about the fundamentals of physics and astronomy, but his careful empirical studies and his systematic and well argued position enormously facilitated the

1 See, for instance, Lloyd, 1987 and Evans, 1996.

2 Suzanne Roux has pointed out to me that the great nineteenth-century British philosopher/scientist William Whewell is an exception. In his historical and philosophical works, Whewell presents Hipparchos and Ptolemy as figures who made the scientific revolution possible through their path-breaking work (Whewell, 1857). However, even Whewell presents Ptolemy's contribution as largely mathematical.

development of a far better account. The second view holds that Archimedes is the greatest ancient scientist because he saw nature in mathematical and geometrical terms and developed a rigorous geometrical methodology which allowed him to discover the fundamental mathematical and geometrical principles of Statics. On this view, the rediscovery of Archimedes' work, and the application of Archimedes' mathematical treatment of nature to kinematics and dynamics, led to the scientific revolution. Galileo's application of Archimedes' methodology to motion is often presented as the pivotal event in the scientific revolution.[3] Neither view sees Hipparchos or Ptolemy as very important scientists.

Since the 1970s, Geoffrey Lloyd and others have argued that Ptolemy's work is the acme of the development of the ancient exact sciences (Lloyd, 1973:113–35; Lloyd, 1987; Taub, 1993). On this account, Ptolemy's system and methodology is probably the finest product of a (largely) post-Aristotelian astronomical tradition mainly developed in Alexandria in Egypt. Ptolemy often used observation and tested his models against observation while avoiding the deeply misleading features of naive observation. Ptolemy also sought mathematical precision and produced an account of reality which was fundamentally geometrical and mathematical. However, unlike Plato and his school, Ptolemy did not fall into the trap of developing a purely *a priori* geometric account of reality.

The part of Ptolemy's work on which I will be focusing is the *Mathematiki Syntaxis* (mathematical compilation), known to Arab and western European scientists as the *Almagest*. Much of that work is a highly technical manual indicating how to calculate astronomical phenomena with reasonable accuracy. I am not competent to discuss any of the technical details as my trigonometry and geometry are elementary. My interest is in what some non-technical parts of the work reveal about Ptolemy's method. I will argue that his arguments for the sphericity of

3 Very roughly, the first view is that of Pierre Duhem and his followers, and the second that of Alexander Koyré and his followers. For a detailed account of these and other views, see Floris Cohen, 1994.

the earth reveal that Ptolemy's methodology resembles the methodology of the modern exact sciences far more than that of Aristotle.

Consider a view recently articulated by Maurice Finocchiaro, one of the foremost authorities on Galileo and the history of early modern science: Aristotle elaborated the physics and astronomical system of the ancient geocentric world view. Ptolemy contributed "primarily the mathematics and the quantitative details of the astronomical system". Finocchiaro admits that Aristotle and Ptolemy differ on the details of the system. But according to him, central arguments, like those proving the sphericity of the earth "were known to Aristotle and can be found in his writings" (Finocchiaro, 1997:8). The view Finocchiaro puts has been widely accepted, perhaps because it underlies the account Thomas Kuhn produced more than forty years ago in his enormously influential textbook, *The Copernican Revolution* (Kuhn, 1957).

As is often the case, Aristotle is given a central role. Yet when one looks at Aristotle's arguments for sphericity, they are weak and not part of a mathematically systematic view. The principal arguments are stated in *On the Heavens* (*Peri Ouranou*).[4] At 294a there is an argument rebutting evidence for the view that the earth is drum shaped. The evidence is that the sun at its setting and rising shows a straight instead of a curved line. Aristotle argues that this evidence is inconclusive. Part of his reasoning is that if the earth's circumference is very great, it will present an appearance of straightness on a very distant object whether it is spherical or not. Quite right. But this does nothing to show that the earth is spherical and neither does Aristotle claim it does.

At 297a there are some *a priori* arguments regarding the natural tendencies of earthly matter – these are scientifically worthless, although Aristotle seems to regard them as primary.

4 I have followed the normal convention in referring to passages in Aristotle, which is to refer to page numbers and column letters of the standard edition of the works of Aristotle, edited by Bekker. These page numbers and column letters are repeated in Aristotle, 1971.

At 297b–298a there are two arguments from observation. The first is that the demarcation line between the light and dark portions of the moon's disc during a lunar eclipse is always convex. According to Aristotle, this shows the sphericity of the earth. As Neugebauer has pointed out, this argument is inconclusive because "there exist an unlimited number of shadow casting and shadow receiving bodies which produce identical shadow limits" – furthermore ancient geometers, like Aristotle's predecessor Eudoxus, would have known this from their geometrical studies and from simple optics (Neugebauer, 1975:1094). For instance, the well known ancient hypothesis that the earth is drum shaped might explain this fact just as well.

The second argument is that as we move north, features of the celestial sphere change. A small change in our position north or south visibly alters the position of stars we see above us. Further, stars visible in the north are not visible in southerly lands such as Egypt or Cyprus. This argument is a little more promising, but it fits reasonably well with the drum shaped earth and, on its own, probably could be fitted around other shapes fairly easily.

All that Aristotle has produced in his arguments from observation is arguments for curvature in one axis (north/south). They are not arguments for constancy of curvature. Perhaps the earth curves to the north in some funny wiggly way. Perhaps the earth curves constantly to the north but is drum shaped. At any rate, there is not enough here to make a case for sphericity. Of course, Aristotle is no fool. He seems to think that the *a priori* arguments do most of the work. But, as I say, they are scientifically worthless.

It might well be possible to put together the two arguments Aristotle presents into a single more powerful argument with the use of a little geometry. However, there is no sign that Aristotle intended anything of the kind in the text. Recently, Geoffrey Lloyd has cast doubt on Aristotle's knowledge of astronomy and on his contribution to astronomy (Lloyd, 1996a:160–83). On Lloyd's account, Aristotle not only made no significant contribution to mathematical astronomy, he showed little awareness of the problems raised for his physics by many empirical facts which were well known to Greek astronomers in Aristotle's time. Insofar as he tries to deal with such problems, his solutions are very poor. If Lloyd is right in thinking that Aristotle's grasp of astronomical matters is weak, he may be garbling a more convincing argument for the sphericity of the earth which had been presented by a contemporary astronomer. However, this is conjecture.

Later Greek scientists presented more rigorous arguments for the sphericity of the earth. Amongst these scientists were Theon of Smyrna and Cleomedes. (Both probably lived in the second century CE.)[5] Ptolemy presents the most rigorous set of arguments (H15–H17).[6] Some of his arguments are also found in Theon or Cleomedes.

Ptolemy starts by trying to find mathematical regularities revealed by the empirical data in order to systematically rule out other possibilities by showing that they cannot plausibly explain the observations. He argues his case both for an east/west direction and a north/south direction. He begins by pointing out that the sun always rises earlier further east. The time of rising is in proportion to the distance between the places involved. We know this, he says, because although lunar eclipses occur at the same real time for all observers, they always occur at a later hour after solar noon for observers further east. This indicates regular curvature (H15).[7]

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5 Ptolemy mentions a Theon as a source of some of his data (H275), but Theon was a common name in the period, so it is unclear whether it is the same Theon. For a brief discussion of these writers, see Evans, 1998:49–51. A problem with Evans is that he believes Aristotle's argument is decisive.

6 I have followed the normal convention in referring to passages in the *Almagest*, which is to refer to pages of the Heiberg edition of the Greek text, which are repeated in Ptolemy, 1984.

7 Toomer points out that "it seems probable the only eclipse observed at places widely separated in longitude for which he [Ptolemy] had records of both observations was the eclipse of – 330 Sept 20 ... observed at Arbela and Carthage" (Ptolemy, 1984:75). (In non-astronomical terms, the lunar eclipse of September 20, 331 BCE observed at Arbela, in the middle of the Persian empire, and Carthage, in the middle of the coast of North Africa.) It would, of course, have been far easier to get data

This argument is followed by arguments which are intended to rule out the other broad possibilities: that the earth is concave, that the earth is plane, that the earth has some polygonal shape. For instance, Ptolemy argues that if the earth were plane, the stars would rise and set for all observers simultaneously (but they do not). Ptolemy rules out the cylindrical or drum shaped earth by tying to his argument for regular curvature in the east/west direction a more elaborate version of the argument advanced by Aristotle for the north/south direction (H16). An important difference is that he stresses the regularity of the phenomena. He tells us that as we move further north, there is a regular change in the stars which are visible.

Ptolemy uses variants of the eliminative methods of induction, discussed in great detail by John Herschel and John Stuart Mill in the nineteenth century. These methods are methods by which a researcher can narrow down a range of causes of an event to one cause. It is widely accepted that the use of these and similar methods is an important part of scientific method.[8] It is difficult to find these methods used at all systematically in Aristotle. Ptolemy not only uses them to argue that the earth is spherical, but also to argue that the heavens move like a sphere, that the earth is in the middle of the heavens and that the earth does not have any

on lunar eclipses observed simultaneously at places which were closer together. Greek and Babylonian astronomers had been regularly observing the heavens for a long time and occasional references to all sorts of observations make clear that Ptolemy had access to a great deal of data. Liba Taub mistakenly cites Toomer in support of the very implausible claim that "Ptolemy probably only had a record of one lunar eclipse observed in two places" (Taub, 1993:71). Puzzlingly, Neugebauer, who is cited correctly by Taub, supports her view (Neugebauer, 1975:938). However, elsewhere Neugebauer states that comments made by Heron in Alexandria in the first century CE indicate that he had no reliable time interval available even for Alexandria and Rome (Neugebauer, 1975:667). This means that Heron had an unreliable time interval for the distance between these two cities. If Heron had such a time interval available, there is little doubt that Ptolemy would have had such time intervals available. All Ptolemy would have needed to support his argument is a few very rough time measurements made at places some distance apart.

8 For recent succinct discussions, see Couvalis, 1997:80–4; Oldroyd, 1986:148–56.

motion from place to place (H10–H26). Of course, he is wrong about all of these claims except the claim that the earth is spherical. But this only shows that the methods are defective if some crucial premises are incorrect. Scientific research is a very risky business in which even the best theories can fail radically. As is well known, Newtonian mechanics is false, even though in 1900 it was the best confirmed theory in the history of science.[9]

I should note that Galen and other post-Aristotelian medical thinkers often used the eliminative methods, even though Galen's methodological position, which is derived from Aristotle, is that medicine should strive for axiomatic demonstration from principles which are obvious *a priori* (Lloyd, 1996b:199–206). However, unlike Galen, Ptolemy's methodological pronouncements are empiricist (Lloyd, 1987; Taub, 1993:44–45).

A second feature of Ptolemy's method is that he thinks he can extrapolate inductively when he finds a rough mathematical regularity (such as that revealed by the local time at which lunar eclipses are observed). From a few of these, he will fill in the gaps and extrapolate to other cases. Finding something that roughly fits a mathematical regularity gives him confidence that he can extrapolate to other cases. This is similar to the method used by various modern physicists or astronomers.[10] By contrast, Aristotle's epagoge (induction) does not contain this mathematical element. Of course, Ptolemy needs to use this type of inductive inference to make his argument work. In deductive logic, it is perfectly consistent with the data he mentions that the earth should be a half sphere, with the antipodes being flat. Further, eliminative induction will not help argue that the antipodes are curved, as he has no knowlede of antipodean astronomical data.

9 See Couvalis, 1997 for detailed discussion of the problems raised for methodology by the failure of Newtonian mechanics.

10 Lloyd points out that sometimes Ptolemy doctors his results in an attempt to squeeze them into neat regularities covered by a law which is formulable in mathematical terms (Lloyd, 1987:246).

A third feature of Ptolemy's method is mathematical idealisation of experience for scientific treatment. He idealises the earth to be a perfect sphere although he knows it is not, because it is such a sphere "as a whole" and mountains etc. are negligible in relation to the size of the earth.[11] Elsewhere, he argues that the ratio of the size of the earth to the distance between the earth and the fixed stars is, *to the senses*, that of a point to any distance. That is to say, the earth is not literally a point, but is so small in relation to the distance between it and the fixed stars that it can be treated mathematically as if it were a point (H20–H21).

Famously, mathematical idealisation is found in Archimedes's works on Statics and Hydrostatics (e.g. Archimedes, 1987:286). It also occurs in many works produced in the post-Aristotelian exact sciences, particularly in Alexandria. As Alexander Koyré pointed out many years ago, such idealisation occurs everywhere in Galileo and Newton. It continues to be a central feature of modern physics. (This is what caused Koyré to argue, somewhat misleadingly, that Galileo and Newton had basically applied Archimedes' methodology to kinematics and dynamics [Koyré, 1965, 1978].) Nancy Cartwright has recently argued very plausibly that mathematical idealisation is necessary for progress in physics and many other sciences (Cartwright, 1983, 1989). Aristotle has little interest in idealisation, though Platonists clearly understand its importance. The trouble with Platonists, unlike Ptolemy, is that they don't understand the importance of testing idealised models against observation.

A close comparison of Aristotle's and Ptolemy's arguments for the sphericity of the earth supports the conclusion that Ptolemy's methodology is far more like that of the modern exact sciences than is the methodology of Aristotle. Ptolemy's argument is also far more convincing. This is further evidence that Ptolemy was not merely a great mathematician, but a scientist of the first order.[12]

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11 Theon of Smyrna produced a "proof" that mountains and depressions on the earth are negligibly small in relation to the size of the earth. For details, see Evans, 1998:51–2.

12 Liba Taub has recently argued very plausibly that Ptolemy's scientific work is

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importantly driven by theological concerns and that its content is partly theological. This in no way prevents Ptolemy's work from being largely scientific. Kepler's and Newton's scientific works are riddled with magical and theological ideas. However, both were great scientists.

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